APPENDIX C

OUTLET PROTECTION DESIGN PROBLEM

C-1. This appendix contains examples of recommended application to estimate the extent of scour in a cohesionless soil and alternative schemes of protection required to prevent local scour.

C-2. Circular and rectangular outlets with equivalent cross-sectional areas that will be subjected to a range of discharges for a duration of 1 hour are used with the following parameters:

Dimensions of rectangular outlet = W_o = 10 feet, D_o = 5 feet

Diameter of circular outlet, D_o = 8 feet

Range of discharge, Q = 362 to 1,086 cubic feet per second

Discharge parameter for rectangular culvert, $q/D_o^{3/2}$ = 3.2 to 9.7

Discharge parameter for circular culvert, $Q/D_o^{5/2}$ = 2 to 6

Duration of runoff event, t = 60 minutes

Maximum tailwater el = 6.4 feet above outlet invert (> 0.5 D_o)

Minimum tailwater el = 2.0 feet above outlet invert (< 0.5 D_o)

Example 1 - Determine maximum depth of scour for minimum and maximum flow conditions:

RECTANGULAR CULVERT (see fig 5-4)

MINIMUM TAILWATER

$$\frac{D_{sm}}{D_o} = 0.80 \left(\frac{q}{D_o^{3/2}}\right)^{0.375} t^{0.10} \qquad \text{(eq C-1)}$$

$$D_{sm} = 0.80\ (3.2 \text{ to } 9.7)^{0.375}\ (60)^{0.1}\ (5) \qquad \text{(eq C-2)}$$

$$= \underline{\underline{9.3 \text{ ft}}} \text{ to } \underline{\underline{14.0 \text{ ft}}}$$

MAXIMUM TAILWATER

$$\frac{D_{sm}}{D_o} = 0.74 \left(\frac{q}{D_o^{3/2}}\right)^{0.375} t^{0.10} \qquad \text{(eq C-3)}$$

$$D_{sm} = 0.74\ (3.2 \text{ to } 9.7)^{0.375}\ (60)^{0.1}\ (5) \qquad \text{(eq C-4)}$$

$$= \underline{\underline{8.6 \text{ ft}}} \text{ to } \underline{\underline{13.0 \text{ ft}}}$$

CIRCULAR CULVERT (see fig 5-4)

MINIMUM TAILWATER

$$\frac{D_{sm}}{D_o} = 0.80 \left(\frac{Q}{D_o^{5/2}}\right)^{0.375} t^{0.10} \qquad \text{(eq C-5)}$$

$$D_{sm} = 0.80\ (2\ \text{to}\ 6)^{0.375}\ (60)^{0.1}\ (8) \qquad \text{(eq C-6)}$$

$$= \underline{\underline{12.5\ \text{ft}}}\ \text{to}\ \underline{\underline{18.9\ \text{ft}}}$$

MAXIMUM TAILWATER

$$\frac{D_{sm}}{D_o} = 0.74 \left(\frac{Q}{D_o^{5/2}}\right)^{0.375} t^{0.1} \qquad \text{(eq C-7)}$$

$$D_{sm} = 0.74\ (2\ \text{to}\ 6)^{0.375}\ (60)^{0.1}\ (8) \qquad \text{(eq C-8)}$$

$$= \underline{\underline{11.6\ \text{ft}}}\ \text{to}\ \underline{\underline{17.5\ \text{ft}}}$$

Example 2 - Determine maximum width of scour for minimum and maximum flow conditions:

RECTANGULAR CULVERT (see fig 5-5)

MINIMUM TAILWATER

$$\frac{W_{sm}}{D_o} = 1.00 \left(\frac{q}{D_o^{3/2}}\right)^{0.915} t^{0.15} \qquad \text{(eq C-9)}$$

$$W_{sm} = 1.00\ (3.2\ \text{to}\ 9.7)^{0.915}\ (60)^{0.15} (5) \qquad \text{(eq C-10)}$$

$$= \underline{\underline{27\ \text{ft}}}\ \text{to}\ \underline{\underline{74\ \text{ft}}}$$

$$W_{smr} = W_{sm} + \frac{W_o}{2} - \frac{D_o}{2} = (27 \text{ to } 74) + \frac{10}{2} - \frac{5}{2} \qquad \text{(eq C-11)}$$

$$= \underline{\underline{29.5 \text{ ft}}} \text{ to } \underline{\underline{76.5 \text{ ft}}}$$

MAXIMUM TAILWATER

$$\frac{W_{sm}}{D_o} = 0.72 \left(\frac{q}{D_o^{3/2}}\right)^{0.915} t^{0.15} \qquad \text{(eq C-12)}$$

$$W_{sm} = 0.72\ (3.2 \text{ to } 9.7)^{0.915}\ (60)^{0.015} \qquad \text{(eq C-13)}$$

$$= \underline{\underline{19 \text{ ft}}} \text{ to } \underline{\underline{53 \text{ ft}}}$$

$$W_{smr} = W_{sm} + \frac{W_o}{2} - \frac{D_o}{2} = (19 \text{ to } 53) + \frac{10}{2} - \frac{5}{2} \qquad \text{(eq C-14)}$$

$$= \underline{\underline{21.5 \text{ ft}}} \text{ to } \underline{\underline{55.5 \text{ ft}}}$$

CIRCULAR CULVERT (see fig 5-5)

MINIMUM TAILWATER

$$\frac{W_{sm}}{D_o} = 1.00 \left(\frac{Q}{D_o^{5/2}}\right)^{0.915} t^{0.15} \qquad \text{(eq C-15)}$$

$$W_{sm} = 1.00\ (2 \text{ to } 6)^{0.915}\ (60)^{0.15}\ (8) \qquad \text{(eq C-16)}$$

$$= \underline{\underline{28 \text{ ft}}} \text{ to } \underline{\underline{76 \text{ ft}}}$$

MAXIMUM TAILWATER

$$\frac{W_{sm}}{D_o} = 0.72 \left(\frac{Q}{D_o^{5/2}}\right)^{0.915} t^{0.15} \qquad \text{(eq C-17)}$$

$$W_{sm} = 0.72\ (2 \text{ to } 6)^{0.915}\ (60)^{0.15}\ (8)$$

(eq C-18)

$$= \underline{\underline{20 \text{ ft}}} \text{ to } \underline{\underline{55 \text{ ft}}}$$

Example 3 - Determine maximum length of scour for minimum and maximum flow conditions:

RECTANGULAR CULVERT (see fig 5-6)

MINIMUM TAILWATER

$$\frac{L_{sm}}{D_o} = 2.40 \left(\frac{q}{D_o^{3/2}}\right)^{0.71} t^{0.125} \qquad \text{(eq C-19)}$$

$$L_{sm} = 2.4\ (3.2 \text{ to } 9.7)^{0.71}\ (60)^{0.125}\ (5)$$

(eq C-20)

$$= \underline{\underline{46 \text{ ft}}} \text{ to } \underline{\underline{101 \text{ ft}}}$$

MAXIMUM TAILWATER

$$\frac{L_{sm}}{D_o} = 4.10 \left(\frac{q}{D_o^{3/2}}\right)^{0.71} t^{0.125} \qquad \text{(eq C-21)}$$

$$L_{sm} = 4.10\ (3.2\ \text{to}\ 9.7)^{0.71}\ (60)^{0.125}\ (5) \qquad \text{(eq C-22)}$$

$$= \underline{\underline{78\ \text{ft}}}\ \text{to}\ \underline{\underline{171\ \text{ft}}}$$

CIRCULAR CULVERT (see fig 5-6)

MINIMUM TAILWATER

$$\frac{L_{sm}}{D_o} = 2.40 \left(\frac{Q}{D_o^{5/2}}\right)^{0.71} t^{0.125} \qquad \text{(eq C-23)}$$

$$L_{sm} = 2.4\ (2\ \text{to}\ 6)^{0.71}\ (60)^{0.125}\ (8) \qquad \text{(eq C-24)}$$

$$= \underline{\underline{52\ \text{ft}}}\ \text{to}\ \underline{\underline{114\ \text{ft}}}$$

MAXIMUM TAILWATER

$$\frac{L_{sm}}{D_o} = 4.10 \left(\frac{Q}{D_o^{5/2}}\right)^{0.71} t^{0.125} \qquad \text{(eq C-25)}$$

$$L_{sm} = 4.10\ (2\ \text{to}\ 6)^{0.71}\ (60)^{0.125}\ (8) \qquad \text{(eq C-26)}$$

$$= \underline{\underline{90\ \text{ft}}}\ \text{to}\ \underline{\underline{195\ \text{ft}}}$$

Example 4 - Determine profile and cross section of scour for maximum discharge and minimum tailwater conditions (see fig 5-8):

CIRCULAR CULVERT

For L_{sm} = 114 ft and D_{sm} = 18.9 ft

L_s/L_{sm}	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
L	0.0	11.4	22.8	34.2	45.6	57.0	68.4	79.8	91.2	102.6	114.0
D_s/D_{sm}	0.7	0.75	0.85	0.95	1.0	0.95	0.75	0.55	0.33	0.15	0.0
D_s	13.2	14.2	16.1	18.0	18.9	18.0	14.2	10.4	6.3	2.9	0.0

For W_{sm} = 76 ft and D_{sm} = 18.9 ft

W_s/W_{sm}	0.0	0.2	0.4	0.6	0.8	1.0
W_s	0.0	15.2	30.4	45.6	60.8	76.0
D_s/D_{sm}	1.0	0.67	0.27	0.15	0.05	0.0
D_s	18.9	12.6	5.1	2.8	0.95	0.0

(Continued)

Example 4 - (Concluded)

RECTANGULAR CULVERT

For L_{sm} = 101 ft and D_{sm} = 14.0 ft

L_s/L_{sm}	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
L	0.0	10.1	20.2	30.3	40.4	50.5	60.6	70.7	80.8	90.9	101.0
D_s/D_{sm}	0.7	0.75	0.85	0.95	1.0	0.95	0.75	0.55	0.33	0.15	0.0
D_s	9.8	10.5	11.9	13.3	14.0	13.3	10.5	7.7	4.6	2.1	0.0

For W_{sm} = 74 ft and D_{sm} = 14.0 ft

W_s/W_{sm}	0.0	0.2	0.4	0.6	0.8	1.0
W_s	0.0	14.8	29.6	44.4	59.2	74.0
D_s/D_{sm}	1.0	0.67	0.27	0.15	0.05	0.0
D_s	14.0	9.38	3.78	2.10	0.70	0.0
$W_{sr} = W_s$						
$W_s + \frac{W_o}{2} - \frac{D_o}{2}$	0-2.5	17.3	32.1	46.9	61.7	76.5

Example 5 - Determine depth and width of cutoff wall:

RECTANGULAR CULVERT, Maximum depth and width of scour = 14 ft and 76.5 ft

From figure 5-8, depth of cutoff wall = $0.7\ (D_{sm}) = 0.7\ (14)$ = 9.8 ft

From figure 5-8, width of cutoff wall = $2\ (W_{smr}) = 2\ (76.5)$ = 153 ft

CIRCULAR CULVERT, Maximum depth and width of scour = 18.9 ft and 76.0 ft

From figure 5-8, depth of cutoff wall = $0.7\ (D_{sm}) = 0.7\ (18.9)$ = 13.2 ft

From figure 5-8, width of cutoff wall = $2\ (W_{sm}) = 2(76)$ = 152 ft

Note: The depth of cutoff wall may be varied with width in accordance with the cross section of the scour hole at the location of the maximum depth of scour. See figures 5-8 and 5-9 of main text.

Example 6 - Determine size and extent of horizontal blanket of riprap:

RECTANGULAR CULVERT

MINIMUM TAILWATER

From figure 5-10, $$\frac{d_{50}}{D_o} = 0.020\ \frac{D_o}{TW}\left(\frac{q}{D_o^{3/2}}\right)^{4/3} \qquad \text{(eq C-27)}$$

$$d_{50} = 0.020\ (5/2)(3.2 \text{ to } 9.7)^{4/3}\ (5) \qquad \text{(eq C-28)}$$

$$= \underline{\underline{1.2 \text{ ft}}} \text{ to } \underline{\underline{5.2 \text{ ft}}}$$

From figure 5-11, $$\frac{L_{sp}}{D_o} = 1.8\left(\frac{q}{D_o^{3/2}}\right) + 7 \qquad \text{(eq C-29)}$$

$$L_{sp} = [1.8(3.2 \text{ to } 9.7) + 7]\ 5 = \underline{\underline{64 \text{ ft}}} \text{ to } \underline{\underline{122 \text{ ft}}} \qquad \text{(eq C-30)}$$

MAXIMUM TAILWATER

$$\frac{d_{50}}{D_o} = 0.020\ \frac{D_o}{TW}\left(\frac{q}{D_o^{3/2}}\right)^{4/3} \qquad \text{(eq C-31)}$$

$$\begin{aligned} d_{50} &= 0.020\ (5/6.4)(3.2 \text{ to } 9.7)^{4/3}(5) \\ &= \underline{\underline{0.37 \text{ ft}}} \text{ to } \underline{\underline{0.76 \text{ ft}}} \end{aligned} \qquad \text{(eq C-32)}$$

$$\frac{L_{sp}}{D_o} = 3\left(\frac{q}{D_o^{3/2}}\right) \qquad \text{(eq C-33)}$$

$$L_{sp} = 3\ (3.2 \text{ to } 9.7)\ 5 = \underline{\underline{48 \text{ ft}}} \text{ to } \underline{\underline{145 \text{ ft}}} \qquad \text{(eq C-34)}$$

CIRCULAR CULVERT

MINIMUM TAILWATER

$$\frac{d_{50}}{D_o} = 0.020\ \frac{D_o}{TW}\left(\frac{Q}{D_o^{5/2}}\right)^{4/3} \qquad \text{(eq C-35)}$$

$$d_{50} = 0.020\ (8/2)(2 \text{ to } 6)^{4/3}\ (8) \qquad \text{(eq C-36)}$$

$$= \underline{\underline{1.6 \text{ ft}}} \text{ to } \underline{\underline{7.0 \text{ ft}}}$$

$$\frac{L_{sp}}{D_o} = 1.8 \left(\frac{Q}{D_o^{5/2}}\right) + 7 \qquad \text{(eq C-37)}$$

$$L_{sp} = 1.8\ (2 \text{ to } 6) + 7 \quad 8 = \underline{\underline{85 \text{ ft}}} \text{ to } \underline{\underline{142 \text{ ft}}} \qquad \text{(eq C-38)}$$

MAXIMUM TAILWATER

$$\frac{d_{50}}{D_o} = 0.020 \frac{D_o}{TW} \left(\frac{Q}{D_o^{5/2}}\right)^{4/3} \qquad \text{(eq C-39)}$$

$$d_{50} = 0.020\ (8/6.4)(2 \text{ to } 6)^{4/3}\ (8) \qquad \text{(eq C-40)}$$

$$= \underline{\underline{0.50 \text{ ft}}} \text{ to } \underline{\underline{2.18 \text{ ft}}}$$

$$\frac{L_{sp}}{D_o} = 3 \left(\frac{Q}{D_o^{5/2}}\right) \qquad \text{(eq C-41)}$$

$$L_{sp} = 3\ (2 \text{ to } 6)\ 8 = \underline{\underline{48 \text{ ft}}} \text{ to } \underline{\underline{144 \text{ ft}}} \qquad \text{(eq C-42)}$$

Use figure 5-12 to determine recommended configuration of horizontal blanket of riprap subject to minimum and maximum tailwaters.

Example 7 - Determine size and geometry of riprap-lined preformed scour holes 0.5- and 1.0-D_o deep for minimum tailwater conditions:

RECTANGULAR CULVERT (see fig 5-10)

0.5-D_o-DEEP RIPRAP-LINED PREFORMED SCOUR HOLE

$$\frac{d_{50}}{D_o} = 0.0125 \frac{D_o}{TW} \left(\frac{q}{D_o^{3/2}}\right)^{4/3} \qquad \text{(eq C-43)}$$

$$d_{50} = 0.0125 \ (5/2)(3.2 \text{ to } 9.7)^{4/3} \ (5) \qquad \text{(eq C-44)}$$

$$= \underline{\underline{0.73 \text{ ft}}} \text{ to } \underline{\underline{3.2 \text{ ft}}}$$

1.0-D_o-DEEP RIPRAP-LINED PREFORMED SCOUR HOLE

$$\frac{d_{50}}{D_o} = 0.0082 \frac{D_o}{TW} \left(\frac{q}{D_o^{3/2}}\right)^{4/3} \qquad \text{(eq C-45)}$$

$$d_{50} = 0.0082 \ (5/2)(3.2 \text{ to } 9.7)^{4/3}(5) \qquad \text{(eq C-46)}$$

$$= \underline{\underline{0.48 \text{ ft}}} \text{ to } \underline{\underline{2.1 \text{ ft}}}$$

CIRCULAR CULVERT

0.5-D_o-DEEP RIPRAP-LINED PREFORMED SCOUR HOLE

$$\frac{d_{50}}{D_o} = 0.0125 \frac{D_o}{TW} \left(\frac{Q}{D_o^{5/2}}\right)^{4/3} \qquad \text{(eq C-47)}$$

$$d_{50} = 0.0125\ (8/2)(2\ \text{to}\ 6)^{4/3}\ (8) \qquad \text{(eq C-48)}$$

$$= \underline{\underline{1.0\ \text{ft}}}\ \text{to}\ \underline{\underline{4.4\ \text{ft}}}$$

1.0-D_o-DEEP RIPRAP-LINED PREFORMED SCOUR HOLE

$$\frac{d_{50}}{D_o} = 0.0082\ \frac{D_o}{TW}\left(\frac{Q}{D_o^{5/2}}\right)^{4/3} \qquad \text{(eq C-49)}$$

$$d_{50} = 0.0082\ (8/2)(2\ \text{to}\ 6)^{4/3}\ (8) \qquad \text{(eq C-50)}$$

$$= \underline{\underline{0.66\ \text{ft}}}\ \text{to}\ \underline{\underline{2.9\ \text{ft}}}$$

See figure 5-13 for geometry.

Example 8 - Determine size and geometry of riprap-lined-channel expansion for minimum tailwaters (see fig 5-15)

RECTANGULAR CULVERT

$$\frac{d_{50}}{D_o} = 0.016\ \frac{D_o}{TW}\left(\frac{q}{D_o^{3/2}}\right)^{4/3} \qquad \text{(eq C-51)}$$

$$d_{50} = 0.016\ (5/2)(3.2\ \text{to}\ 9.7)^{4/3}\ (5) \qquad \text{(eq C-52)}$$

$$= \underline{\underline{0.94\ \text{ft}}}\ \text{to}\ \underline{\underline{4.1\ \text{ft}}}$$

CIRCULAR CULVERT

$$\frac{d_{50}}{D_o} = 0.016 \ \frac{D_o}{TW}\left(\frac{Q}{D_o^{5/2}}\right)^{4/3} \qquad \text{(eq C-53)}$$

$$d_{50} = 0.016\ (8/2)(2 \text{ to } 6)^{4/3}\ (8) \qquad \text{(eq C-54)}$$

$$= \underline{\underline{1.29 \text{ ft}}} \text{ to } \underline{\underline{5.6 \text{ ft}}}$$

See figure 5-14 for geometry.

Example 9 - Determine length and geometry of a flared outlet transition for minimum tailwaters:

RECTANGULAR CULVERT

$$\frac{L}{D_o} = 0.30\left(\frac{D_o}{TW}\right)^2\left(\frac{q}{D_o^{3/2}}\right)^{2.5(TW/D_o)^{1/3}} \qquad \text{(eq C-55)}$$

$$L = 0.3\ (5/2)^2\ (3.2 \text{ to } 9.7)^{2.5(2/5)^{1/3}}\ 5 \qquad \text{(eq C-56)}$$

$$= \underline{\underline{80 \text{ ft}}} \text{ to } \underline{\underline{616 \text{ ft}}}$$

CIRCULAR CULVERT

$$\frac{L}{D_o} = \left[0.30\left(\frac{D_o}{TW}\right)^2\left(\frac{Q}{D_o^{5/2}}\right)^{2.5(TW/D_o)^{1/3}}\right] \qquad \text{(eq C-57)}$$

$$L = \left[0.3\ (8/2)^2\ (2 \text{ to } 6)^{2.5(2/8)^{1/3}}\right] 8 \qquad \text{(eq C-58)}$$

$$= \underline{\underline{114 \text{ ft}}} \text{ to } \underline{\underline{645 \text{ ft}}}$$

See figure 5-16 for geometric details; above equations developed for H - 0 or horizontal apron at outlet invert elevation without an end sill.

Example 10 - Determine diameter of stilling well required downstream of the 8-ft-diam outlet:

From figure 5-17

$$\frac{D_W}{D_o} = 0.53 \left(\frac{Q}{D_o^{5/2}}\right)^{1.0} \qquad \text{(eq C-59)}$$

$$D_W = 0.53\ (2 \text{ to } 6)\ 8 = \underline{\underline{8.5 \text{ ft}}} \text{ to } \underline{\underline{25.4 \text{ ft}}} \qquad \text{(eq C-60)}$$

See figure 5-17 for additional dimensions.

Example 11 - Determine width of US Bureau of Reclamation type VI basin required downstream of the 8-ft-diam outlet:

From figure 5-18

$$\frac{W_{VI}}{D_o} = 1.30 \left(\frac{Q}{D_o^{5/2}}\right)^{0.55} \qquad \text{(eq C-61)}$$

$$W_{VI} = [1.3\ (2 \text{ to } 6)^{0.55}]\ 8 \qquad \text{(eq C-62)}$$

$$= \underline{\underline{15.2 \text{ ft}}} \text{ to } \underline{\underline{27.9 \text{ ft}}}$$

See figure 5-18 for additional dimensions.

Example 12 - Determine width of SAF basin required downstream of the 8-ft-diam outlet:

From figure 5-19

$$\frac{W_{SAF}}{D_o} = 0.30 \left(\frac{Q}{D_o^{5/2}}\right)^{1.0} \qquad \text{(eq C-63)}$$

$$W_{SAF} = 0.30\ (2\ \text{to}\ 6)\ 8 = \underline{\underline{4.8\ \text{ft}}}\ \text{to}\ \underline{\underline{14.4\ \text{ft}}} \qquad \text{(eq C-64)}$$

See figure 5-19 for additional dimensions.

Example 13 - Determine size of riprap required downstream of 8-ft-diam culvert and 14.4-ft-wide SAF basin with discharge of 1,086 cfs

$$q = \frac{Q}{W_{SAF}} = \frac{1086}{14.4} = 75\ \text{cfs/ft} \qquad \text{(eq C-65)}$$

$$V_1 = \frac{Q}{A} = \frac{1086}{0.785(8)^2} = 21.6\ \text{fps} \qquad \text{(eq C-66)}$$

$$d_1 = \frac{q}{V_1} = \frac{75}{21.6} = 3.5\ \text{ft} \qquad \text{(eq C-67)}$$

$d_2 = 8.4$ ft (from conjugate depth relations)

MINIMUM TAILWATER REQUIRED FOR A HYDRAULIC JUMP = 0.90 (8.4) = 7.6 ft

$$d_{50} = D \left(\frac{V}{\sqrt{gD}}\right)^3 \qquad \text{(eq C-68)}$$

$$V = \frac{q}{D} = \frac{75}{7.6} = 9.9 \text{ fps} \qquad \text{(eq C-69)}$$

$$d_{50} = 1.0 \left[\frac{9.9}{\sqrt{32.2(7.6)}}\right]^{3} 7.6 \qquad \text{(eq C-70)}$$

$$d_{50} = \underline{\underline{1.9 \text{ ft}}} \qquad \text{(eq C-71)}$$